New results from the DANSS experiment

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There are several experimental indications of sterile neutrinos with a mass in the 1 eV ballpark and many experiments are trying to clarify the situation. During 6 years the DANSS experiment collected more than 6 million inverse beta decay events and measured the background level during 4 reactor-off periods. Data were collected at 3 distances (10.9 m, 11.9 m, and 12.9 m) from the center of the core of a 3.1 GW_{th} reactor with event rate up to 5 thousand per day. The detector position was changed frequently usually 2-3 times a week. Therefore many systematic uncertainties were canceled out in the analysis. After collection of additional 0.7 million anti-neutrino events the significance of the best-fit point in the 4ν case increased from 1.3σ to 2.35σ. This is still not statistically significant and we present the exclusion area that covers a very interesting range of the sterile neutrino parameters up to $\sin^2 2\theta_{ee} < 0.004$ in the most sensitive point. In particular the DANSS experiment excludes a large fraction of sterile neutrino parameters preferred by the recent BEST experiment results including its best-fit point. The inverse beta decay event rate dependence on the fuel composition was measured. It agrees with predictions of the Huber-Mueller model. During almost 6 years the reactor power was measured with $\approx 1.8\%$ accuracy in 2 days using the anti-neutrino event rate normalized to the reactor power at the initial period.

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1. Introduction

The deficit of ν_e in the calibration of the SAGE and GALLEX experiments with radioactive sources [1, 2] ("Gallium Anomaly"(GA)) and the deficit in reactor $\tilde{\nu}_e$ fluxes [3, 4] ("Reactor Antineutrino Anomaly"(RAA)) can be explained by active-sterile neutrino oscillations.

RAA can be explained by new measurements [5, 6] of beta spectra of fission products of ^{235}U and ^{239}Pu that give 5.4% smaller ratio than previous results used for predictions of reactor $\tilde{\nu}_e$ fluxes [3, 4].

Recently the BEST experiment [7, 8] confirmed GA with more than 5σ significance. For $\Delta m^2_{41} < 5\text{eV}^2$ very large values of $\sin^2 2\theta_{ee} \approx 0.4$ preferred by BEST are excluded by DANSS [9, 10] and NEOS [11]. For $\Delta m^2_{41} > 5\text{eV}^2$ the BEST results are in tension with several other experiments [8].

The MiniBooNE collaboration [12] confirmed the LSND results [13] on $\nu_e(\tilde{\nu}_e)$ appearance in the $\nu_\mu(\tilde{\nu}_\mu)$ beams with a combined significance of 6σ. Appearance of electron neutrinos in muon neutrino beams can be explained by sterile neutrinos. The MicroBooNE collaboration has not confirmed the MiniBooNE results but has not excluded them completely [14].

The Neutrino-4 experiment claimed an observation of sterile neutrinos although the significance of the result was only 2.7σ [15, 16] and there were concerns about the validity of their analysis (see e.g. [17]).

The survival probability of reactor $\tilde{\nu}_e$ at very short distances in the 4ν mixing scenario (3 active and 1 sterile neutrino) is given by the formula:

$$1 - \sin^2 2\theta_{ee} \sin^2(1.27\Delta m^2_{41}[\text{eV}^2]L[\text{m}]/E_\nu[\text{MeV}]),$$

where $\sin^2 2\theta_{ee}$ is the mixing parameter, $\Delta m^2_{41} = m^2_4 - m^2_1$ is the difference in the squared masses of neutrino mass states, L is the distance between production and detection points and E_ν is the $\tilde{\nu}_e$ energy. The Inverse Beta Decay (IBD) reaction $\tilde{\nu}_e + p \rightarrow e^+ + n$ is used to detect $\tilde{\nu}_e$. In this reaction $E_\nu \approx E_{e^+} + 1.8$ MeV.

2. Detector, data analysis and positron spectra.

The DANSS detector [18] is located on a movable platform under the core of a 3.1 GW$_{th}$ reactor of the Kalininskaya nuclear power plant in Russia. It is made of 2.5 thousand $100 \times 4 \times 1$ cm^3 scintillator strips with Gd-loaded surface coating. Strips in neighbor layers are orthogonal. This allows a quasi-3D reconstruction of events. Three wavelength-shifting fibers placed in grooves along the strip are used to collect the scintillation light. The central fiber is read out with a Silicon Photomultiplier (SiPM) and the two side fibers from 50 parallel strips are readout with a compact photomultiplier tube. External backgrounds are suppressed by a multi-layer active and passive shielding. The kinetic energy of the reconstructed positron is used in the analysis that is 1.02 MeV smaller than the prompt energy used in other experiments. This approach does not depend on energies of annihilation gammas that have a nonlinear energy response.

The SiPM's gains and cross-talks vary with temperature. They are calibrated every 25–30 minutes using noise signals collected in parallel with data taking. The energy responses of all 2500 scintillator counters are calibrated every 2 days using cosmic muons. A median of the Landau distribution is used in the analysis since it is more stable than the most probable value.

The detector energy scale is fixed with the ^{12}B beta spectrum measured using two ^{12}B production mechanisms: μ^- captures on carbon and neutron interactions with carbon. The lifetime of ^{12}B coincides nicely with the expected $\tau = 29.1$ ms in both cases (28.6 ± 0.7 ms and 29.4 ± 0.6 ms correspondingly). The energy scales agree in both cases within $\pm 0.2\%$. The energy scale that is determined using ^{60}Co and ^{248}Cm radioactive sources agrees within $\pm 0.2\%$ with the ^{12}B scale. The response to the ^{22}Na source is 1.8% lower than expected probably because of many soft gammas from this source that are not well enough described by the DANSS Monte Carlo. Such soft gammas are rare in positron and ^{12}B events. Nevertheless, we still use in the analysis a 2% uncertainty in the energy scale.

The accidental coincidence background is calculated in a model independent way using time intervals for neutron signals preceding the positron signal. Several cuts [19, 20] reduce the accidental background to 15.3% of the IBD signal at the top detector position for the positrons in the (1.5-6) MeV energy interval used in the oscillation analysis. Other background estimates below use the same conditions. The background from neighbor reactors is 0.6% only and has a known shape. Other correlated backgrounds were estimated using 4 reactor-off periods to be less than 1.8%.
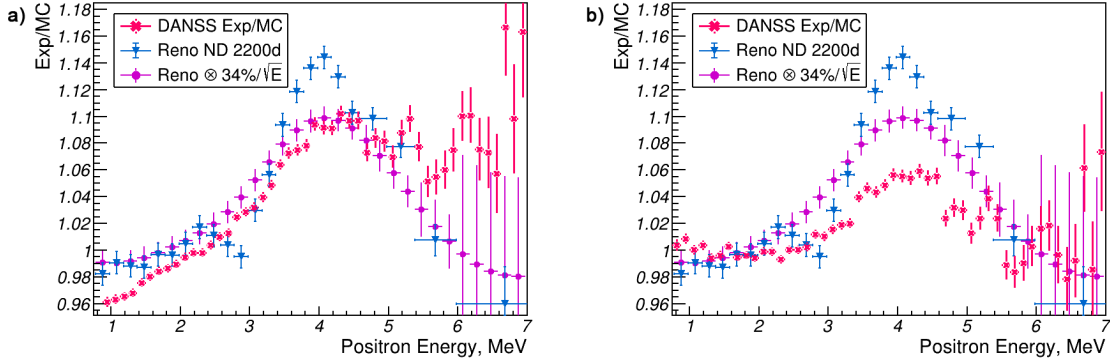

Figure 1: a) Experiment to the H-M model MC ratio for e^+ spectrum; b) the same ratio with e^+ energy shifted by -50 keV.

A ratio of the measured positron spectrum and the Huber-Mueller (H-M) model [3, 4] MC predictions is shown in Fig. 1a as well as the RENO results [21] shifted by -1.02 MeV to take into account the difference between the e^+ kinetic energy used by DANSS and the prompt energy used by RENO. The RENO spectrum smeared by the DANSS energy resolution is also shown. The best agreement between our measurements and the Monte Carlo (MC) predictions in the range $1.5 - 3.0$ MeV is obtained if the e^+ energy is shifted by -50 keV which is within the systematic uncertainties (Fig. 1b). In this case we observe a bump similar in shape and position with the RENO bump smeared by the DANSS resolution. However the height of the bump is considerably smaller. Because of the high sensitivity of the measured ratio to the energy scale and shifts we can not claim the existence of the bump. The results of other experiments which claim the existence of the bump should be also very sensitive to the energy scale and possible shifts.

The relative IBD rate dependence on the ^{239}Pu fission fraction for different positron energies (see Fig. 2a) agrees with the H-M model MC predictions and slightly larger in absolute values than the Daya Bay measurements [22]. The reactor power was measured using the anti-neutrino

counting rate corrected for the changes in the efficiency and fuel composition according to the H-M model with the accuracy of 1.8% in 2 days during almost 6 years (see Fig. 2b). The IBD event rate was normalized to the reactor power during an initial one month period in 2016. The rate at the different detector distances to the reactor core center was scaled taking into account the differences in the solid angle that is almost proportional to $1/L^2$.
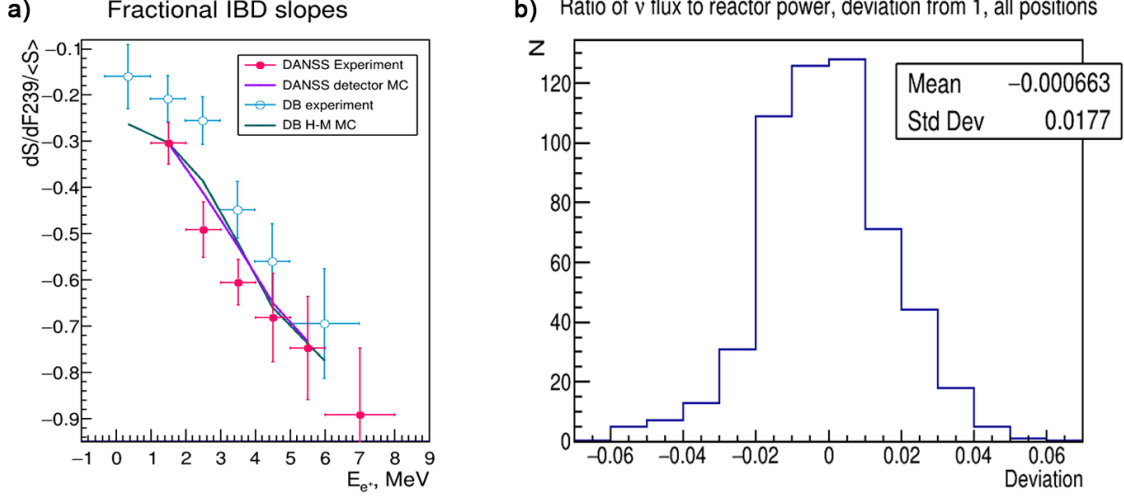

Figure 2: a) Relative IBD rate dependence on the ^{239}Pu fission fraction for different e^+ energies; b) Relative difference between IBD event rate in about 2 day periods and the reactor power during the reactor operation at full power.

3. Search for sterile neutrinos.

In the search for sterile neutrinos we use only ratios of positron spectra at the different distances from the reactor core. Systematic uncertainties in the energy scale and backgrounds were treated as nuisance parameters in the test statistics [23]. With additional 0.7 million IBD events collected in 2021 and 2022 the significance of the best-fit point in the 4ν case ($\Delta m^2_{41} = 0.35\text{eV}^2$, $\sin^2 2\theta_{ee} = 0.07$) increased from 1.3σ to 2.35σ. There is another point ($\Delta m^2_{41} = 1.3\text{eV}^2$, $\sin^2 2\theta_{ee} = 0.02$) with a very similar significance. The significance levels for the 4ν hypothesis obtained with the Feldman-Cousins method are shown in Fig. 3a. Still the indications in favor of the sterile neutrino are not statistically significant and we use the Gaussian CL$_s$ approach [24] to obtain the exclusion area shown in Fig. 3b that covers a very interesting range of the sterile neutrino parameters up to $\sin^2 2\theta_{ee} < 0.004$ in the most sensitive point. In particular a large part of the sterile neutrino parameters preferred by the recent BEST results [7, 8] is excluded including the BEST best-fit point (see Fig. 3c).

The DANSS collaboration has started the upgrade of the detector that should extend the sensitivity to higher Δm^2_{41} values and will allow to scrutinize even larger fraction of the BEST preferred area of the sterile neutrino parameters as well as the Neutrino-4 result. However, the plans for the upgrade are delayed due to external problems.
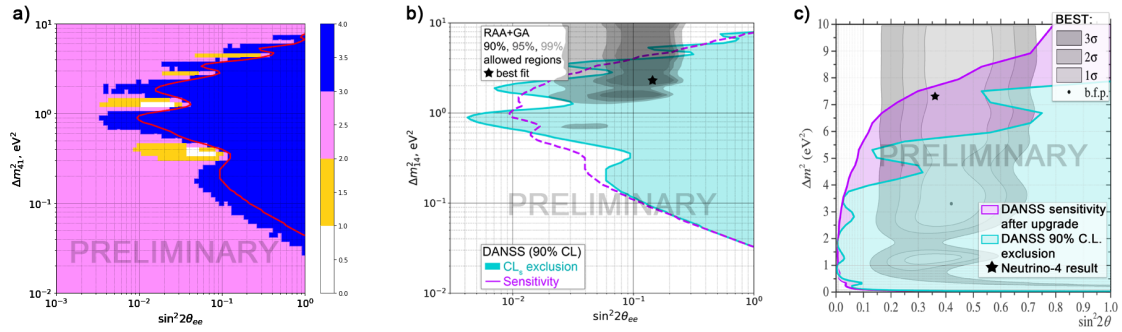
Figure 3: a): Confidence levels for 4ν hypothesis at 1σ, 2σ, 3σ, and 4σ obtained using the Feldman-Cousisns method, the red line corresponds to the 3σ exclusion contour obtained using the Gaussian CL_s method; b): 90% C.L. exclusion area (cyan) obtained with the Gaussian CL_s method in comparison with the RAA+GA expectations; c): The same exclusion area in comparison with the BEST results [7, 8] and expected DANSS sensitivity after the upgrade.

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